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Quantification and mapping of the supply of and demand for carbon storage and sequestration service in woody biomass and soil to mitigate climate change in the socio-ecological environment

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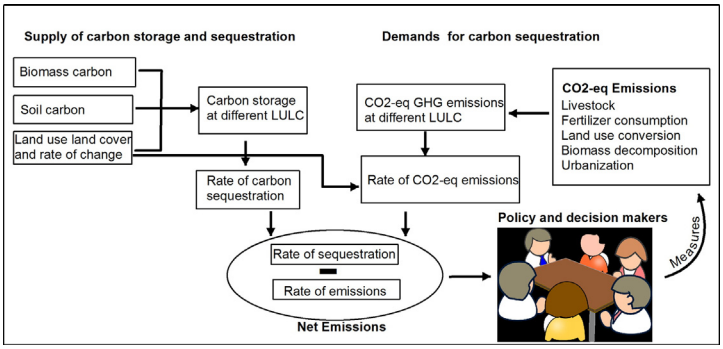
HIGHLIGHTS

- Information on the regulatory capacity of ecosystems is needed to manage ecosystem services.
- The balance between net ecosystem services can be mapped in a spatially explicit manner.
- An ecosystem which has a large carbon storage may not exhibit a high carbon sequestration.
- Net negative GHG emissions can be produced in the socio-ecological environment.
- Supply-demand balance of carbon sequestration provide information to decision makers in mitigating climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, the supply of and demand for carbon storage and sequestration of woody biomass in the socio-ecological environment of the Wabe River catchment in Gurage Mountains, Ethiopia, were estimated. This information was subsequently integrated into a map that showed the balance between supply capacities and demand in a spatially explicit manner to inform planners and decision makers on methods used to manage local climate change. Field data for wood biomass and soil were collected, satellite images for land use and land cover (LULC) were classified, and secondary data from statistics and studies for estimation were obtained. Carbon storage, the rate of carbon sequestration and the rate of greenhouse gas (GHG) emissions from diverse sources at different LULCs, was estimated accordingly by several methods. Even though a large amount of carbon was stored in the catchment, the current yearly sequestration was less than the CO_2-eq. GHG emissions. Forest and Enset-based agroforestry emissions exhibited the highest amount of woody biomass, and cereal crop and wetland exhibited the highest decrease in soil carbon sequestration. CO_2-eq. GHG emissions are mainly caused by livestock, nitrogenous fertilizer consumption, and urban activities. The net negative emissions were estimated for the LULC classes of cereal crop, grazing land, and urban areas. In conclusion, without any high-emission industries, GHG emissions can be greater than the regulatory capacity of ecosystems in the socio-ecological environment. This quantification approach can provide information to policy and decision makers to enable them to tackle climate change at the root level. Thus, measures to decrease emission levels and enhance the sequestration capacity are crucial to

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mitigate the globally delivered service in a specific area. Further studies on the effects of land use alternatives on net emissions are recommended to obtain in-depth knowledge on sustainable land use planning.

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1. Introduction

Ecosystems regulate the climate on different geographical scales ranging from the modification of the temperature at local scales to influencing the warming of our planet on the global scale by providing sources or sinks of greenhouse gases (GHG) and aerosols (Betts, 2000). However, with the rapidly changing economic growth, population or demographic, and land use and land management, GHG have been observed to be greater than the regulatory functionality of the different components of an ecosystem (IPCC, 2001). The terrestrial ecosystem, which is the major biological sink of atmospheric carbon dioxide, has become one of the main sources of CO_2 emissions on account of anthropogenic activities (Schulze, 2006). Agriculture, forestry, and related land uses are the major contributing factors to climate change, accounting to approximately 25% of anthropogenic GHG emissions, originating mainly from deforestation and agricultural emissions from livestock, soil, and nutrient management (Smith et al., 2014).

Although the quantification of carbon stocks from biomass and soil and GHG emissions from different sectors are the most commonly studied regulatory ecosystem services (Brown et al., 1989; IPCC, 2006; Tubiello et al., 2014), obtaining realistic localized data estimates in several geographical regions has been in the developmental stage. Most of the available data do not show the supply and demand across the different LULCs in an explicit manner to enhance the understanding of decision makers in mitigating climate change (Zhao and Sander, 2015), probably related to the fact that the supply and demand of ecosystem services have been examined only recently (Bagstad et al., 2013; Schulp et al., 2014; Sturck et al., 2014). Typically, quantification and mapping have focused on service supply rather than demands because the demand-side quantification of regulating services is particularly challenging as these services are neither directly used nor consumed (Zhao and Sander, 2015). In addition, a majority of the studies lack a spatial component and are quantified on a large scale. However, these data are crucial for capturing the complete climate regulation ecosystem service dynamic moving from service supply to demand. Hence, it is crucial to estimate the potential of the ecosystems sequestering CO_2 from the atmosphere as a supply and emissions from anthropogenic and natural sources, making more GHG concentrations in the atmosphere, as a demand in a spatially explicit manner (Zhao and Sander, 2015). This estimation can help policy makers in identifying the locations at which policies might be targeted as well as land use planners in being vigilant during planning (Baro et al., 2014). In particular, this estimation is beneficial for countries in which land use changes constitute the main problems.

In sub-Saharan Africa, land use change has been reported to be the primary source of CO_2 emissions (Vagen et al., 2005). According to the type of LULC conversion and the management measures carried out, carbon stocks are positively or negatively affected as these stocks directly act on the exchanges of GHG between terrestrial ecosystems and the atmosphere (Zhu et al., 2010). Owing to severe soil degradation and desertification, the rate of soil carbon sequestration has decreased, and carbon emissions from the soil in semi-arid and sub-humid parts of the region have increased. However, studies have revealed significant local variations (Vagen et al., 2005).

Meanwhile, land use within the Gurage Mountains of Ethiopia is primarily oriented to subsistence agriculture (Woldetsadik, 2004). During the 1930s, ~20% of the landscape areas in the Gurage Mountains were covered with natural forests. Since then, these forests have been decreasing, and the removal has been particularly rapid from 1991 to 1992 because of the political system change in the country (Bekalu and Feleke, 1996). On account of these LULC changes, the ecosystems that provide regulatory ecosystem services are deteriorating. However, information related to the potential of the mountains to regulate climate change and emission levels of the different agricultural and socio-economic activities in the mountains is not available. Nevertheless, it is crucial to assess the demand and supply of climate regulation ecosystem services, including these mountains, agricultural, forest, and other land use landscape areas as such areas are highly sensitive to process changes. In turn, these systems could potentially create uncertainties on the level and value of ecosystem services supplied in the future (Sil et al., 2017).

Thus, this study aimed (1) to assess the supply of and demand for carbon storage and sequestration in woody biomass and (2) to identify the gap between the supply of and demand for this ecosystem service in a spatially explicit manner so as to provide information to local policy and decision makers to mitigate climate change from the sources in the Wabe River catchment of Gurage Mountains. A relatively higher coverage of vegetation in the mountains was observed in this catchment, with highly dynamic LULCs.

2. Material and methods

2.1. Study area

The Gurage Mountains extend from the Awash River Basin in the North to the Hadya zone in the South, partitioning the Gurage zone in half. The mountains form a watershed boundary between the Omo–Gibe River Basin in the West and the Great East African Rift Valley in the East. The Wabe River catchment is a sub-basin of the Omo–Gibe. The catchment is located between 08°21′ and 08°30′ N and 38°05′ and 37°49′ E. The Gurage Mountains, with altitudes of 3611 m above sea level, account for the highest area in the catchment, and the lowest altitude of 1014 m is found in the western Gibe River (Fig. 1). The catchment covers a drainage area of 1860 km^2. The maximum temperature of the Wabe River catchment ranges from 20 °C (in the wet season) to 39 °C (in the dry season), and the minimum temperature ranges from 0 °C to 19 °C, with an average temperature of 18 °C. The mean annual rainfall ranges from 1200 to 1320 mm. Land use within the Wabe River catchment is primarily oriented to Enset-based subsistence agriculture, although an increase in the plantation of eucalyptus trees and Khat (*Catha edulis*), as well as cereal cultivation, has been reported (Woldetsadik, 2004). Enset crop plants constitute the main food source in the Gurage Mountains area.

2.2. Data collection

2.2.1. Woody biomass data

Woody biomass data were collected on site from forest, shrubland, woodland, and Afro-Alpine vegetation LULCs in the catchment by a mixed stratified preferential sampling method to ensure full coverage of environmental variation and habitat heterogeneity. Google Earth and SPOT imageries were utilized to identify the clear distinction between vegetation and habitat heterogeneity. Using ArcGIS software, eight transects ranging between 11 and 80 km in length and 5 km in width were laid along the altitudinal gradient line. At places in which non-vegetation land cover was found along the transect line, sample plots were laid by the deviation of the transect line to obtain a vegetation cover. At each transect, sample plots of 20 m × 20 m were laid at an altitude difference of 100 m. However, in areas where a high variation in the vegetation cover and habitat heterogeneity was observed,

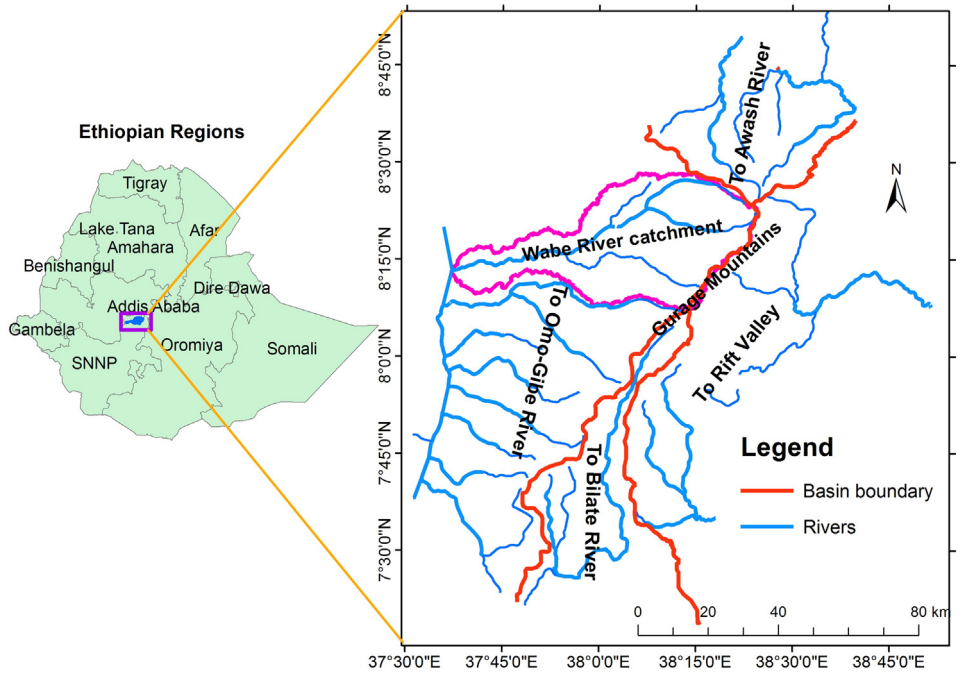

Fig. 1. Location map of the Wabe River catchment.

more than one sample plot was laid within an altitude difference of 100 m by preference sampling techniques. Within each sample plot, all woody species with a diameter at breast height (DBH, 1.3 m above the ground) >5 cm were measured for their DBH. In total, 90 sample plots were examined (Fig. 2).

2.2.2. Soil sampling

Soil samples were collected from the grazing land, Enset-based agroforestry, crop land, wetland, bare land, Afro-Alpine vegetation, natural forest, eucalyptus plantation, shrubland, woodland, and built-up LULCs. Similar to the sampling of woody biomass, eight transects ranging between 11 and 80 km in length and 5 km in width were laid along the altitudinal gradient line, and sample plots were laid at an interval of 2.5 km. During sampling surveys, some of the sample plot locations deviated from the transect line to include important LULCs. In the vegetation land cover, soil samples were collected from the woody biomass sampling sites. In plot areas containing similar soil, samples were not collected from the woody biomass sampling sites. The wetland soil samples were collected during the dry season when no water was available and the soil was dry, and in the built-up area, soil samples were collected between buildings with no vegetation cover and from peripheral open areas. Soil samples were collected from four sites within the quadrant areas of 20 m × 20 m from depths of 30 cm, and ~100 g of composite samples was taken to the laboratory. Meanwhile, undisturbed samples were collected using a core sampler size of 10 cm × 10 cm to determine the bulk density. In total, soil was collected from 105 sample plots (Fig. 2). From the collected sample data, the percentages of carbon and bulk density were determined in the Wolkite soil laboratory.

2.2.3. LULC data

The LULC and its changes data in the Wabe River catchment were obtained from the supervised classification of Landsat images of 1986 (TM) and 2017 (TIROS) using ERDAS Imagine software. Before classification, pre-image-processing operations such as image restoration,

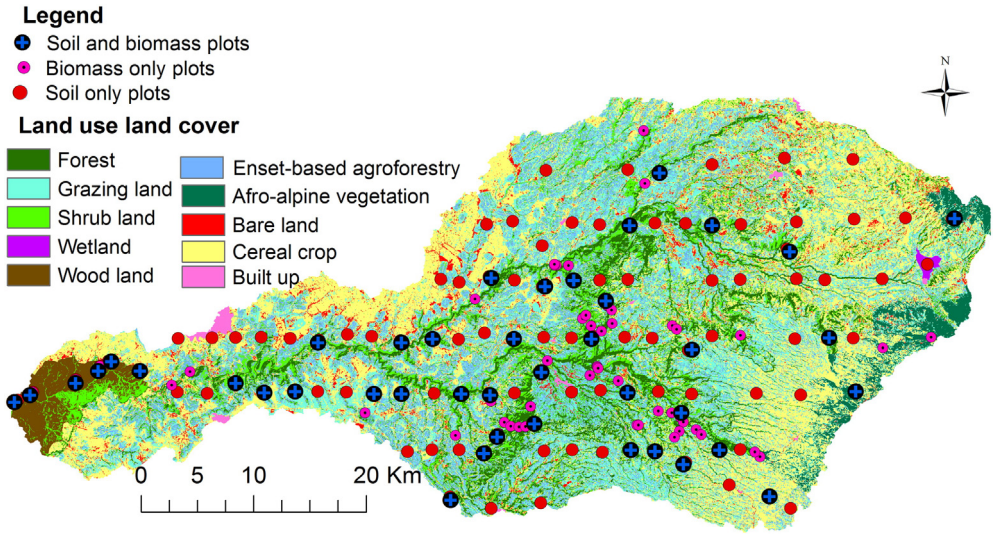

Fig. 2. Soil and woody biomass sample plot collection locations in the Wabe River catchment.

georeferencing, and image enhancement were carried out. Accuracy was assessed using accuracy assessment tools in the software by utilizing representative points after classification. These points were collected from the field using GPS and visual interpretation of the raw images with the guidance of personal knowledge of the study area and high-resolution imageries such as Google Earth, SPOT, and Sentinel 2. Classification was carried out with overall accuracies of 91.6% and 87.7% for the 1986 and 2017 images, respectively. The identified major 10 LULCs included the grazing land, Enset-based agroforestry, crop land, wetland, bare land, built-up area, Afro-Alpine vegetation, forest land, shrubland, and woodland (Table 1). Among these LULCs, grazing land and cereal crop covered larger areas (Fig. 2).

2.2.4. Secondary data

Woody biomass data for the cereal crop, grazing land, urban area, and Enset farm were obtained from the results of the woody biomass stock inventory in Ethiopia (WBISPP, 2004). In this inventory, the average woody biomass for each LULC was estimated. Although the WBISSP (2004) data were collected 13 years ago, the study assumed that significant changes in the biomass of species in the low-vegetation cover area of the study area were not occurred in the last decade. In fact, the woody biomass inventory report is the only recent and comprehensive document available for the country. Recently, the inventory report has been used for the forest assessment of the country (Global Forest Resources Assessment (FRA), 2005, 2010). To estimate livestock emissions, data regarding the livestock population of the study area were obtained from the 2014/15 socio-economic abstract of the Gurage Zone (GZFED, 2015), and their default emission value was taken from IPCC (2006). Different statistical and literature data used to estimate other emission sources were listed in the data analysis section.

2.3. Carbon stocks

In this study, only the carbon stock available in woody biomass and soil was considered as these pools are the major sources of carbon in terrestrial ecosystems (Watson, 2008).

2.3.1. Carbon stock in woody biomass

To estimate the above-ground woody biomass, different mathematical equations have been developed and used (Brown et al., 1989; Negi et al., 1988). The model developed by Brown et al. (1989) was used in this study because the life zone of the study area corresponds to that recommended for the equation. This allometric equation (Eq. (1)) is suitable for areas with an annual rainfall of <1500 mm and a vegetative stem >5 cm DBH.

$$Y = 34.4703 - 8.0671\ (DBH) + 0.6589\left(DBH^2\right) \quad (1)$$

here, Y is above-ground biomass, and DBH is the diameter at breast height.

For estimating below-ground biomass, a root-to-shoot ratio was used (MacDicken, 1997). This below-ground biomass was estimated by the multiplication of the above-ground biomass by a factor of 0.27, which is recommended to Afromontane forest (IPCC, 2006).

As the study area was part of the tropical and sub-tropical regions, the biomass stock density of a sampling plot was converted to carbon stock densities after the multiplication with an IPCC (2006) default carbon fraction of 0.5 as the dry biomass contained 50% organic carbon.

Next, the carbon stock in biomass was converted into CO_2 equivalent by Eq. (2):

$$CO_2\text{—eq.} = \text{biomass C} \times 3.67 \quad (2)$$

2.3.2. Carbon stock in soil

The core method (Blake and Hartge, 1986) was employed to determine the bulk density, and soil organic carbon was determined by the Walkley–Black oxidation method (Schnitzer, 1982). Then, the total soil organic carbon was determined using Eq. (3):

$$SOC = BD \times D \times \%C \quad (3)$$

here, SOC = soil organic carbon stock per unit area (t ha^{-1}), BD = soil bulk density (g cm^{-3}), D = the total depth at which the sample was collected (30 cm), and %C = carbon concentration (%).

Then, the total carbon stocks in each LULC were determined from the respective woody biomass of vegetation and soil carbon.

2.4. Supply of carbon sequestration

The carbon sequestration rate (supply) of the catchment LULCs was obtained from carbon sequestration in woody biomass and soil.

2.4.1. Woody biomass carbon sequestration

Woody biomass carbon sequestration was determined from the growth rate of woody biomass. The growth rate of each LULC woody biomass datum was obtained from the estimated woody biomass stock inventory of Ethiopia (WBSIE) at different LULCs (WBISPP, 2004). In WBSIE, the growth rate is 1% in the Afro-Alpine vegetation to 6% in the crop land and built-up area. Forest, grazing land, and shrubland LULCs exhibited growth rates of 4.5%, 4%, and 3.5%, respectively. Enset crop land use exhibited a 5% woody biomass growth rate. The woody biomass growth rate was not considered for wetland and bare land herein because of the absence of wood biomass in these catchment LULCs.

2.4.2. Soil carbon sequestration

Soil carbon sequestration was estimated using land management data, corresponding to the conversion probability of LULCs in the Wabe River catchment and the estimated global land use conversion value reported by Deng et al. (2016). Data regarding the LULC conversion probability were obtained from the LULCs of 1986 and 2017 using

Table 1
Description of the identified LULC in the Wabe River Catchment.

LULC	Description
Bare lands	Areas of land that have been degraded either due to erosion or over grazing and crop cultivation.
Grazing lands	All areas covered with grass and used for livestock grazing
Cereal crops	Areas of land prepared for growing cereal crops. This category includes areas currently under crop, and land prepared for cereal cultivation
Forests	Areas covered by trees, natural or planted with a minimum size of 0.5 ha.
Woodlands	Area with open stand of trees, mainly dominated by *Acacia* spp.
Built up	Urban fabrics of residential, commercial, industrial, transportation other land
Shrub land	The area covered by small trees, bushes, and shrubs and mixed with grasses; less dense than forests
Wetland	Areas that are waterlogged and swampy in the wet season, and relatively dry in the dry season
Enset-based agroforestry	Areas dominated by Enset crop mixed with fruit trees, vegetables, *Khat*, coffee, etc. and growing in the home garden
Afro-alpine vegetation	High altitude vegetation dominated by a shrub *Erica arborea,* herbs and grasses.

Land Use Change Modular for ArcGIS (LCM). The output of LCM was the probability of one LULC to the other classes (Table 2). To make the work simpler and to match with the value assigned by Deng et al. (2016), land uses were first grouped into a more generalized LULC of three classes, namely, agriculture and settlement (includes cereal, Enset-based agroforestry, bare land, and built-up area), grassland (includes grazing land and wet land), and vegetation (includes forest, shrubland, woodland, and Afro–Alpine vegetation). According to Deng et al. (2016), soil carbon stocks significantly increase after the conversion from farmland to grassland by a rate of 0.3 tons ha^{-1} $year^{-1}$ and forest to grassland by a rate of 0.68 tons ha^{-1} $year^{-1}$. After conversions of farmland to forest and grassland to forest, soil carbon stocks did not change significantly. Then, the soil sequestration rate of one LULC herein was obtained by considering the average value of the change of one LULC to the other land uses.

2.5. Demands for carbon sequestration

To determine the demands of carbon sequestration, different CO_2 sources were identified, and their emission contribution was accordingly estimated using several methods. The emission sources herein include the burning and decomposition of woody biomass, land use conversions (soil), livestock, fertilizer use, and urbanization.

2.5.1. Emissions from woody biomass

A 2% annual mortality rate of woody biomass assumed in the woody biomass inventory (based on an average maximum age of trees/shrubs of 50 years) was considered herein to estimate the carbon losses each year (WBISPP, 2004). A 100% emission of the carbon stored in trees is assumed to be emitted into the atmosphere within a year of death. This assumption is made because the main source of energy in this study area is woody biomass, and the other sources of energy account to <20%. As agricultural landscapes account for the majority of the catchment, farmers mainly use dead wood for fire wood. According to the wood biomass strategy of Ethiopia, the highest fuel wood consumption per capita of the country is in Enset-dominant livelihood zones that contain this catchment.

2.5.2. Emissions from soil

The soil carbon emission rate herein was estimated using the conversion probability of LULC in the Wabe River catchment similar to the carbon sequestration rate (Table 2). According to Deng et al. (2016), soil carbon stocks considerably decreased after the conversion from grassland to farmland by a rate of 0.89 tons ha^{-1} $year^{-1}$, forest to farmland by a rate of 1.74 tons ha^{-1} $year^{-1}$, and forest to forest by a rate of 0.63 tons ha^{-1} $year^{-1}$. Soil carbon stocks do not considerably change after the conversion of farmland to forest and grassland to forest. By this analysis, the remaining LULCs did not exhibit any CO_2 emissions and assigned a zero value.

2.5.3. Emissions from livestock

Livestock emits methane by enteric fermentation and manure management. Methane emissions from enteric fermentation were estimated from Eq. (4) (based on Eq. (10.19) of the 2006 IPCC Guidelines) for different livestock sub-categories. The sum of the emissions from the seven livestock categories (i.e., donkey, horse, mule, cattle, goat, sheep, and poultry) represents the total methane emissions from enteric fermentation for this study area.

$$\text{Emissions} = \text{EF}\,(\text{T}) \times \text{N}\,(\text{T})/10^3) \quad (4)$$

here, emissions = methane emissions from enteric fermentation, tons of CH_4/year; EF (T) = emission factor for the defined livestock population, kg CH_4/head/year; N (T) = the number of head of livestock species/category T in the country; and (T) = species/category of livestock.

The emission factors corresponding to each livestock sub-category for enteric fermentation were all IPCC default values related to developing countries (Table 3) (IPCC, 2006). According to this report, the default value for poultry was under development. For this study, the value was calculated from the manure management result because the study reported by Gerber et al. (2013) revealed that 80% of emissions from poultry are caused by enteric fermentation. The methane emissions resulting from Eq. (4) were then multiplied by 21, representing the global warming potential for methane at 100 years in the atmosphere, to yield the carbon dioxide equivalent in tons of CO_2 equivalent (IPCC, 2006).

The same formula as that used for enteric fermentation was used to estimate the CO_2 emissions from manure management, but the emission factors from Table 3 were used. The emission factors varied depending on temperature, and for this study, the value assigned by Brown et al. (2012) for Ethiopia based on an average temperature was used. The EFs were estimated on the basis of the assumption that a majority of the manure for most of the livestock is deposited on the open grazing lands, with a small amount (<4%) burned as fuel in Africa (Brown et al., 2012). Similar conditions were utilized in this study area, but the manure was deposited on Enset-based agroforestry rather than on the grazing land.

2.5.4. Nitrous oxide emissions from the use of nitrogenous fertilizers

Herein, the average nitrogenous fertilizer consumption of Ethiopia was used, and the direct and indirect emissions from the use of nitrogenous fertilizers were estimated. The direct N_2O–N emissions in tons N_2O–N were estimated from Eq. (5):

$$N_2O\text{Direct} = \text{EF}\,(N_2O\text{–N}) \times \text{N}\,(\text{NF}) \times 44/28 \quad (5)$$

here, N_2ODirect = direct nitrous oxide emissions from the consumption of nitrogenous fertilizers; tons N_2O/year, EF (N_2O–N) = emission factor for N_2O–N (= 0.01, dimensionless), N (NF) = consumption of nitrogenous fertilizers; tons N/year, in the country, 44/28 = conversion of N_2O–N emissions to N_2O.

Table 2
The probabilities of changes between LULC.

Probabilities of changing to										
LULC	Enset	Cereal crop	Grazing land	Bare land	Shrub land	Forest	Built up	Afro- alpine	Wet land	Wood land
Enset	0.67	0.13	0.13	0.01	0.06	0	0	0	0	0
Cereal crop	0.09	0.56	0.21	0.08	0.04	0.01	0.01	0	0	0
Grazing land	0.14	0.39	0.37	0.04	0.03	0.01	0	0.02	0	0
Bare land	0.11	0.40	0.05	0.07	0.26	0.10	0	0.01	0	0
Shrub land	0.28	0.05	0.02	0	0.44	0.16	0	0	0	0.04
Forest	0.04	0.08	0.01	0.01	0.25	0.59	0	0.02	0	0
Built up	0	0	0	0	0	0	0.99	0	0	0
Afro-alpine	0.05	0.38	0.18	0.02	0.02	0.01	0	0.35	0	0
Wetland	0.02	0.02	0.04	0	0.01	0	0.02	0	0.9	0
Wood land	0	0	0	0	0.16	0	0	0	0	0.84

NB: Afro-alpine = Afro-alpine vegetation and Enset = Enset-based agroecology.

Table 3
Default IPCC emission factors for enteric fermentation and manure management (kg CH_4/head/yr) customized to Ethiopia.

Region	Donkey	Cattle	Goats	Mules	Horses	Sheep	Poultry
Enteric fermentation	10	31	5	10	18	5	–
Manure management	0.9	1.0	0.17	0.9	1.64	0.15	0.02

A global warming potential of 298 (for 100 years) was used to convert to tons of CO_2-eq. GHG.

Indirect N_2O–N emissions in t N_2O–N were estimated as the product of direct emissions and fraction lost by leaching and runoff ($Frac_{LEACH}$). A default value of 0.05 from IPCC was used as the average evapotranspiration that exceeds the rainfall in Ethiopia (Brown et al., 2012).

2.5.5. Emissions from urbanization

The activities found in urban areas exert their own impact on GHG emissions. For the towns in the study area, the customized estimated value of GHG emissions per hectare for Addis Ababa was used (AACA, 2015). As the emission sources in the urban areas were similar, emissions from energy, transportation, and waste were considered. Emissions from industries were not considered because of their absence in the catchment.

Finally, emission source values were assigned to the respective emission sources of a specific LULC and added together to obtain the total emissions of CO_2-eq. GHG per year in the catchment.

2.6. Balance of supply and demand

The supply–demand balance analysis was carried out using the supply and demand data and map. First, supply and demand maps were produced using the results of sequestration and emission data. Then, the demand map was subtracted from the supply map to produce a map showing the balance between supply and demand.

3. Results

3.1. Carbon stocks

3.1.1. Woody biomass carbon stock

a. Carbon stock per tree

The results obtained from the carbon stock assessment revealed that the average stock per tree varies from 0.006 to 1.36 tons. The average carbon storage for all species was 0.12 tons. The highest average stock available per species per individual tree was recorded for *Ficus vasta* (1.36 tons), *Acacia senegal* (0.93 tons), *Osyris quadripartita* (0.91 tons), *P. africana* (0.74 tons), and *Hagenia abyssinica* (0.7 tons). The lowest carbon stock of 0.006 tons was recorded for *Premna schimperi*. The most frequent species of *Juniperus procera*, *Podocarpus falcatus*, and *P. africana* exhibited a higher carbon stock compared to the other species. Average carbon stocks of 0.9, 0.7, and 0.6 tons were observed for the families of the Santalaceae, Rosaceae, and Moraceae species per individual tree, respectively, which were greater than those of the other family species, whereas the Vitaceae, Thymelaeaceae, and Lamiaceae families exhibited a lower average carbon stock. In addition, the study revealed that the average carbon stock is higher for trees compared to shrubs. The average carbon stock for the tree species (0.15 tons) was considerably greater than that for the shrub species (0.035 tons). The carbon stock amount was directly related to the DBH classes. Trees with a higher DBH exhibited large stocks and vice versa.

b. Carbon stock within vegetation types

The average carbon stock investigated for all vegetation types of woody biomass was 16 ± 20.8 tons ha^{-1}. The Afro-Alpine vegetation with an average 1.9 ± 2.1 tons ha^{-1} exhibited the lowest carbon stock of all vegetation types. Woodland exhibited the second lowest stock. Eucalyptus plantations exhibited an average of 4.5 ± 7.9 tons ha^{-1}. Shrubland exhibited an average stock of 2.9 ± 8.9 tons ha^{-1}. The largest stock of carbon was investigated in church forests (51.5 ± 29.4 tons ha^{-1}). Mixed (7.7 ± 8.3 tons ha^{-1}) and riverine (11 ± 12.6 tons ha^{-1})-type forests exhibited an intermediate amount of carbon stock in the catchment.

c. Carbon stock in low-vegetation LULCs

The WBSIE has estimated that the land use biomass in different classes depends on the biomass density within specific land uses. The comparison of the WBSIE estimation with this study's woody biomass estimation based on collected field data revealed some exaggeration made by WBSIE. Thus, the low-density value set by the inventory is considered for those LULCs of this study in which data are not collected in the field. Accordingly, 1.5 tons ha^{-1} of carbon stock was available from the tree woody biomass of the cereal crop farm land. In the grazing land, 1.58 tons ha^{-1} of carbon stock was estimated. Built-up areas exhibited a lower carbon stock of 0.75 tons ha^{-1} in the survey. The bare land and wetland of the Wabe River catchment did not have any trees. Thus, zero above and below-ground carbon stock is considered even though the woody biomass stock inventory sets an average value.

d. Effect of the altitude on the woody biomass carbon stock

Altitudes affected the carbon stock of the vegetation in the Wabe River catchment, and the highest average stock of 20 tons ha^{-1} was investigated at altitudes ranging between 2500 and 3000 m. Then, altitudes ranging between 2000 and 2500 m exhibited the next stock with 16.7 tons ha^{-1}. Altitudes <2000 m exhibited an average carbon stock of 8.4 tons ha^{-1}. The lowest carbon stock was available in the Afro-Alpine shrub vegetation areas with an altitude >3000 m.

3.1.2. Soil carbon stock

a. Soil organic carbon (SOC)

Results obtained from the soil sample data analysis revealed that the percent of carbon concentration varies between the lowest of 0.2% and the highest of 12.7%. The average percent of carbon concentration for the whole sample was 3.4%. The bulk density of soil in the catchment ranged between 0.4 and 1.2, with a mean of 0.9. On account of the variation in the bulk density and carbon concentration, the SOC exhibited large ranges, with the minimum of 6.6 tons ha^{-1} and the maximum of 251 tons ha^{-1}. The average SOC for all LULCs and altitudes was 93 ± 4.8 tons ha^{-1}.

b. SOC in different LULCs

Results revealed that soil samples collected from different LULCs exhibit a variation in the SOC amount. Even though the Afro-Alpine vegetation covers exhibited the lowest area coverage, they exhibited the highest stock in terms of SOC. An average carbon stock of 173.2 ± 77 tons ha^{-1} was available in this land cover, with the minimum and maximum of 118.4 and 228 tons ha^{-1}, respectively. Natural forests exhibited the second-largest SOC stock (122.6 ± 71 tons ha^{-1}). The cereal crop SOC amount varied from the lowest of 32 tons ha^{-1} to the highest of 198.4 tons ha^{-1}, with an average of 100.3 ± 43 tons ha^{-1}. Grazing land was one of the LULCs that exhibited a higher mean SOC of the catchment (93 ± 4.8 tons ha^{-1}), with an average of 95.1 ± 64 tons ha^{-1}. The lowest SOC (6.6 tons ha^{-1}) was observed in this LULC. On the Enset crop farm, a mean of 93.5 ± 41 tons ha^{-1} of SOC was investigated.

Shrubland (73.7 ± 39 tons ha^{-1}) was one of the lowest SOC potential LULCs herein. The lowest average SOC (41.9 ± 11 tons ha^{-1}) was investigated in eucalyptus plantations, with the maximum of 63.2 tons ha^{-1} and the minimum of 28.6 tons ha^{-1} SOC. In addition, low SOC was recorded for the bare land and built-up area.

c. Total carbon stocks

As shown in Fig. 3 and Table 4, among the LULCs, the Afro-Alpine vegetation cover exhibited the highest average total carbon stock of 175 ± 78 tons ha^{-1} mainly because of the highest SOC. Forest land (109 ± 104 tons ha^{-1}) exhibited the second-largest carbon stock with the combination of the highest woody biomass and soil organic carbon. Woodland, cereal crop, and Enset-based agroforestry, exhibiting an almost similar carbon stock, were ranked as the third highest. Bare land and built-up areas exhibited the lowest carbon stock, with 72 ± 11 and 70 ± 0.5 tons ha^{-1}, respectively.

As shown in Table 4, the total amount of carbon stock in the catchment was 18,691,500 tons and can offset 68,597,700 tons of CO_2-eq. GHG. On account of its larger area coverage, crop land exhibited the largest stock.

3.2. Supply of carbon sequestration

3.2.1. Woody biomass carbon sequestration rate

The highest growth rate of woody biomass carbon was observed for forest land (0.72 tons ha^{-1} year^{-1}, Table 5). Enset-based agroforestry (0.34 tons ha^{-1} year^{-1}) exhibited the second-highest growth rate of the woody biomass carbon in the Wabe River catchment (Fig. 4). The Afro-Alpine vegetation exhibited one of the lowest growth rates for woody biomass carbon with a value of 0.02 ha^{-1} year^{-1}. As no trees were present in the bare land and wetland, biomass exhibited no change. The average growth rate of woody biomass carbon from all LULCs was 0.16 tons ha^{-1} year^{-1}.

3.2.2. Soil carbon sequestration rate

On the basis of the land conversion probability of the Wabe River catchment and the value obtained from Deng et al. (2016) for land use conversion, soil carbon sequestration increased for the Afro-Alpine vegetation, bare land, and Enset-based agroforestry by 0.3 tons ha^{-1} year^{-1} (Table 5), and it decreased for the other LULCs, except for shrubland, which exhibited no change. The largest carbon sequestration was investigated in Enset-based agroforestry, and each year, 21,059 tons of carbon was sequestered (Table 5). Forest land demonstrated a potential for sequestering 12,456 tons year^{-1}. In total, 49,796 tons of carbon was sequestered in the Wabe River catchment every year, which can offset 182,750 tons of CO_2-eq. GHG in the atmosphere.

3.3. Demand for carbon sequestration

3.3.1. Emission from woody biomass

The highest mortality or removal rate of woody biomass was observed for forest and Enset-based agroforestry, with 1.17 and 0.7 tons ha^{-1} year^{-1} CO_2 emissions, respectively. Built-up and grazing land exhibited lower tree removal rates compared to other LULCs. Thus, less CO_2 emissions are produced. On account of the woody biomass removal and mortality, 58, 284 tons year^{-1} of CO_2 is completely produced in the Wabe River catchment.

3.3.2. Emission from soil

The highest decrease in the soil carbon sequestration was observed for the cereal crop and wetland, with each emitting 3.27 tons ha^{-1} year^{-1} of CO_2. The soil carbon sequestration for the forest, woodland, and grazing land LULCs decreased, with each emitting CO_2 at a rate of 1.18 tons ha^{-1} year^{-1}. On account of the land use conversion, 261,346 tons of CO_2 emissions was produced in the catchment.

3.3.3. Emission from livestock

Emissions from enteric fermentation and manure management constitute one of the greatest sources of agricultural GHG emissions in the catchment. Of the six districts of the catchment and Wolkite town, 1235,626 livestock were observed overall (Table 6). From this value, cattle and poultry accounted for the largest values, corresponding to 48% and 24% of the livestock, respectively. Methane emitted by enteric fermentation compared to manure management was dominant (96%). From both sources, 88.3% of the emissions originated from cattle. Even though a large number of sheep and goat were present in the catchment, they together contributed to 6% of the livestock emissions. Horse, mule, and donkey contributed to 5.7% of the methane emissions from enteric fermentation and manure management in the catchment. Compared to the number of poultry in the catchment, its contribution to GHG was insignificant. In total, 136,462 and 4956 tons year^{-1} of CH_4 were emitted from the districts of catchment from enteric fermentation and manure management, respectively. In total, 136,440 tons of CH_4 was emitted from grazing land, and 3.79 tons of CH_4 was emitted in each hectare per year in the catchment. The remaining 4578 tons of CH_4 originated from Enset-based agroforestry because most of the manure deposited on this crop.

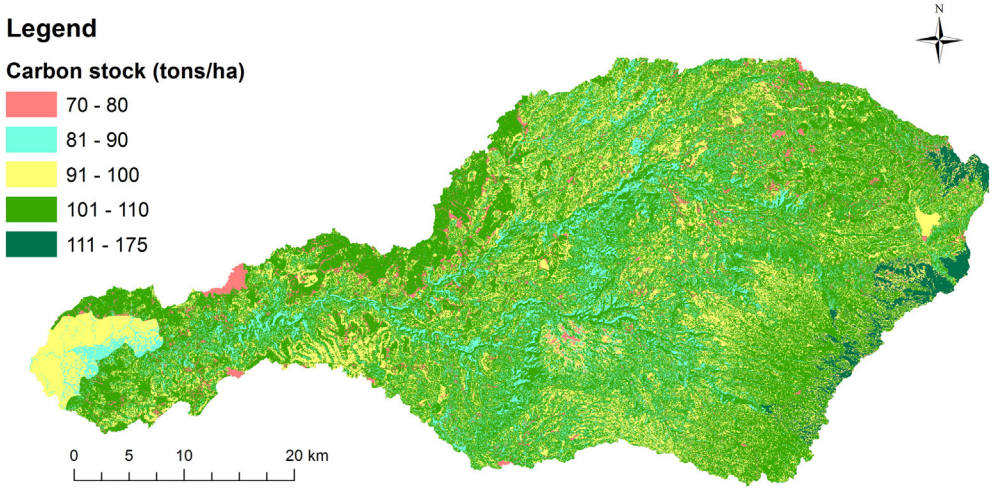

Fig. 3. Spatial distribution of carbon stock in the Wabe River catchment.

Table 4
The total carbon stock in different LULC.

LULC	Biomass C (tons ha^{-1})	Soil TOC tons ha^{-1}	Average C (tons ha^{-1})	Area (ha)	Total C (tons)	CO_2-eq. (tons)
Afro-alpine vegetation	1.78	173.2	175 ± 78	4700	822,500	3,018,600
Bare land	0	72.1	72 ± 11	6900	503,700	1,848,600
Cereal crop	1.5	100.3	102 ± 46	60,400	6,160,800	22,610,100
Enset-based agroforestry	6.88	93.5	100.4 ± 53	32,700	3,283,000	12,048,900
Forest land	16	122	109 ± 104	17,300	1,885,700	6,920,500
Grazing land	1.58	95.1	96.7 ± 70	36,000	3,481,200	12,776,000
Shrub land	5.53	84.4	90 ± 48	23,000	2070,000	7,596,900
Built up	0.75	69.3	70 ± 0.5	800	56,000	205,520
Wetland	0	95.1	95 ± 3	300	28,500	104,600
Wood land	2.16	97.8	100 ± 52	4000	400,000	1,468,000
Total					18,691,500	68,597,700

3.3.4. Emission from the use of nitrogenous fertilizers

According to the statistical report of Ethiopia, the average consumption of fertilizers in Ethiopia was 0.53 tons $year^{-1}$ in 1 ha of cereal crop land (CSA, 2015). From this value, the majority of the fertilizer consumed was diammonium phosphate, and the nitrogenous fertilizer urea accounted for only 45% of the total fertilizer consumption. Thus, ~-0.24 tons $year^{-1}$ of nitrogenous fertilizers is used. The catchment has 60,400 ha of cereal crop land, with the total consumption of 14,496 tons $year^{-1}$. On the basis of this amount of consumption, 67,882 tons of CO_2-eq. GHG from direct and 3394 tons of CO_2-eq. GHG from indirect means were emitted each year in the catchment, implying that 1.18 tons of CO_2-eq. GHG is emitted per year in every hectare of the cereal crop.

3.3.5. Emission from urbanization

According to the GHG emission estimated for Addis Ababa, on average, 44.4 tons of CO_2-eq. GHG was emitted in 1 ha of built-up area each year from the energy, transportation, and waste sectors (Table 7). On the basis of this value, the towns in this catchment emitted 35,520 tons of CO_2-eq. GHG per year.

On the basis of the emission source analysis, the LULCs exhibited different emission ranges from low in bare land (zero) to the highest built-up area (45.6 tons ha^{-1} $year^{-1}$) (Fig. 5). Cereal crop emitted the second-highest amount of GHG (4.56 tons ha^{-1} $year^{-1}$). The Afro-Alpine vegetation, Enset-based agroforestry, and shrubland exhibited relatively lower amounts of emissions of 0.13, 0.64, and 0.41 tons ha^{-1} $year^{-1}$, respectively. Forest land emitted 2.35 tons ha^{-1} $year^{-1}$. Because of its large area and high-emission capacity, crop land ranked the first from the catchment LULC, with an emission of 275,424 tons $year^{-1}$. Grazing land emitted 178,920 tons $year^{-1}$. Even though the coverage of the built-up area was insignificant, it contributed to 36,512 tons ha^{-1} $year^{-1}$ of the catchment emissions.

3.4. Carbon sequestration supply versus demand

Even though a large amount of carbon was stocked in the Wabe River catchment, the current yearly sequestration was less than the CO_2-eq. GHG emissions (Table 8). The supply-to-demand difference revealed that a net 380,368 tons $year^{-1}$ of CO_2-eq. GHG is emitted into the atmosphere by different LULCs. The largest net negative emissions were observed for the crop and grazing lands (Fig. 6). The built-up areas in the catchment contributed to the net negative emissions of 36,380 tons $year^{-1}$. The Afro-Alpine vegetation, bare land, Enset-based agroforestry, shrubland, and woodland exhibited a net positive carbon sequestration. The largest net positive sequestration was observed in Enset-based agroforestry. Even though these LULCs exhibited a net positive carbon sequestration, the three LULCs (i.e. built-up areas, crop and grazing lands) exhibited a far greater emission and produced to exhibit a net negative sequestration in the catchment.

4. Discussion

4.1. Carbon stock

The global biomass carbon stock in tropical dry and wet forests ranged between 13 and 123 and 95–528 tons ha^{-1}, respectively (Murphy and Lugo, 1986). In the Amazon rainforest in Brazil, the global biomass carbon stock ranged between 130 and 223 tons ha^{-1} (Alves et al., 1997). The carbon stock reported herein ranged between 1 and 154 tons ha^{-1}, with an average of 16 ± 20.8 tons ha^{-1}; this value is less than those reported for various mixed, old growth, and evergreen moist tropical forests (Brown, 1997). Furthermore, this value is less than those reported for the Egdu forest (Feyissa et al., 2013), Menagesha Suba forest (Sahle, 2011), selected church forests in Addis Ababa (Tura et al., 2013), and the Tara Gadam forest (Gedefaw et al., 2014) in Ethiopia because these forests were well conserved with relative low disturbance, and

Table 5
The rate of carbon sequestration at different LULC.

LULC	Biomass seq. (tons ha^{-1} yr^{-1})	Soil seq. (tons ha^{-1} yr^{-1})	Total seq. (tons ha^{-1} yr^{-1})	Area (ha)	Carbon seq. (tons yr^{-1})	CO_2-eq. (tons yr^{-1})
Afro-alpine vegetation	0.02	0.3	0.32	4700	1494	5482
Bare land	0	0.3	0.3	6900	2070	7597
Cereal crop	0.09	0	0.09	60,400	5436	19,950
Enset-based agroforestry	0.34	0.3	0.64	32,700	21,059	77,286
Forest land	0.72	0	0.72	17,300	12,456	45,714
Grazing land	0.06	0	0.06	36,000	2275	8350
Shrub land	0.19	0	0.19	23,000	4452	16,338
Built up	0.05	0	0.05	800	36	132
Wetland	0	0	0	300	0	0
Wood land	0.13	0	0.13	4000	518	1903
Total					49,796	182,750

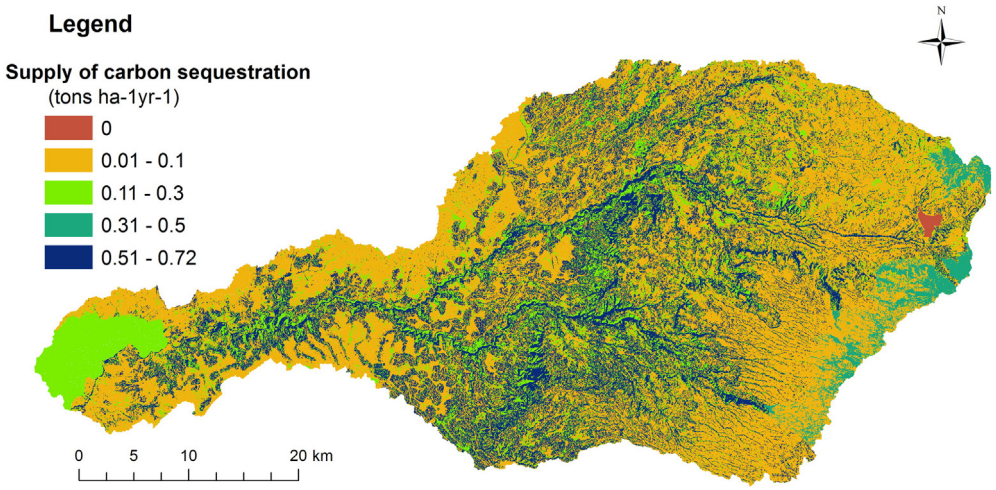

Fig. 4. Supply of carbon sequestration in the Wabe River catchment.

the vegetation in the Wabe River catchment was founded in agricultural landscapes with human interferences.

The difference in the woody biomass carbon stock in the catchment LULCs resulted from the variation in the existence of woody biomass stock in each LULC. The LULC with high woody biomass, such as church forests, exhibited high carbon stock. The woody biomass in land uses such as grazing land, crop land, and bare land was rare, and the woody biomass carbon stock amount was less. The significant effect of the woody biomass carbon stock herein was consistent with other studies that have reported a negative correlation between tree biomass and carbon storage at altitudes (Sharma et al., 2009; Moser et al., 2007; Sheikh et al., 2012). The middle altitude exhibited the highest woody biomass carbon storage, and low carbon storage observed at high altitude was similar to studies in Ethiopia (Feyissa et al., 2013; Yohannes et al., 2015). The low stock in the low catchment resulted from the fact that the majority of the stand trees/shrubs exhibited low biomass.

In addition, several studies have explained that land use affects SOC stocks, and soils under vegetation cover consist of high organic carbon (Abera and Belachew, 2011; Habtamu et al., 2014; Haile et al., 2014). A higher stock was observed for the Afro-Alpine vegetation herein, which was related to the presence of high-biomass shrubs such as *Erica arborea* species and grasses and the relatively good soil depth. Several years of non-human interferences of the area, except for grazing purposes, contributed to the remains of the dead biomass in the area and conversion into soil, possibly rendering the cover area soil with high organic carbon. However, shrubland and woodland exhibited a low SOC. With respect to the agricultural land use types in Ethiopia, agroforestry exhibited a higher mean soil carbon storage compared to grazing land and cereal cultivation (Gebeyehu et al., 2017). However, herein, cereal crop land exhibited a higher SOC compared to a majority of the LULCs, revealing that SOC depends not only on land use types but also on various local factors, including climatic conditions, soil properties, and land use and management practices.

Eucalyptus plantation areas exhibited a low SOC herein similar to that reported previously. Liang et al. (2016) have reported that eucalyptus plantations have lower organic matter compared to mixed and natural forests in northern Ethiopia. According to Lemenih et al. (2004), sites with eucalyptus exhibit increased soil acidity, and the base saturation decreases compared to the native vegetation sites and adjacent agricultural lands. Another study by Turner and Lambert (2000) in Brazil revealed that the content of the soil organic carbon in eucalyptus plantations is less than that in the adjacent native vegetation site because the litter fall of the species takes a long time to decompose and the species do not permit the growth of other species.

Soil organic carbon globally increases with precipitation and clay content, although it is mainly determined by carbon output (decomposition) and decreases with increasing temperature (Zhu et al., 2010). Low sequestration rates were observed under the coolest and warmest conditions. Sites in the warm and middle-temperature regions tend to accumulate soil carbon more rapidly than those in cold regions, whereas semi-humid areas exhibit higher sequestration rates compared to their semi-arid counterparts (World Bank, 2012). Even though SOC was not consistent herein, it relatively increased with altitude. The result is in agreement with the forest soil carbon density in Beijing (Xiao et al., 2014) and in Karakoram mountain ranges of Pakistan (Shedayi et al., 2016).

4.2. Carbon sequestration

Currently, it is difficult to obtain carbon sequestration rates in different LULCs. A few measurements available in natural and plantation forests have been cited in the IPCC, 2006 report (IPCC, 2006). Seasonal tropical rain forests in the Amazon (Grace et al., 1995) and dense, moist rain forests (Fan et al., 1990; Malhi et al., 1999) exhibit approximately 1 ton ha^{-1} $year^{-1}$ and 2 and 5.9 tons ha^{-1} $year^{-1}$, respectively. Sample plot studies also revealed that the net carbon sequestration rates in selectively logged evergreen rain forests and in heavily logged rain forests are 2.9 and 2.4 tons ha^{-1} $year^{-1}$, respectively (Nabuurs and Mohren, 1993). Herein, the forest carbon sequestration (0.72 tons ha^{-1} $year^{-1}$) was in agreement with the 0.7–1.5 tons ha^{-1} $year^{-1}$ for semi-evergreen tropical rainforests (Malhi et al., 1999). In plantation forests of China, previous studies have revealed total annual

Table 6
Number of livestock with their enteric fermentation and manure management in Wabe River catchment.

Livestock	Cattle	Sheep	Goat	Horse	Mule	Donkey	Poultry	Total	Emission of CH_4 (tons ha^{-1} yr^{-1})
No. of livestock	593,145	155,862	95,749	31,413	3404	51,912	304,141	1235,626	
Enteric fermentation	18,387	779	479	565	34	519	24	20,764	3.79
Manure management	593	23	16	52	3	47	6	740	0.14
Total	18,981	803	495	617	37	566	30	21,504	3.93
%	88.3	3.7	2.3	2.9	0.2	2.6	0.14	100.0	

Table 7
CO_2-eq. GHG emissions (tons ha^{-1} yr^{-1}) from different sources.

LULC	Biomass	Soil	Livestock	Fertilizer	Urbanization	Total emission
Afro-alpine vegetation	0.13	0	0	0	0	0.13
Bare land	0	0	0	0	0	0
Cereal crop	0.11	3.27	0	1.18	0	4.56
Enset-based agroforestry	0.5	0	0.14	0	0	0.64
Forest land	1.17	1.18	0	0	0	2.35
Grazing land	0.12	1.18	3.79	0	0	1.85
Shrub land	0.41	0	0	0	0	0.41
Built up area	0.06	1.18	0	0	44.4	45.6
Wetland	0	1.18	0	0	0	1.18
Wood land	0.16	1.18	0	0	0	1.34
Total (tons)	58, 284	260,719	141,018	71,277	35,520	
%	11%	51%	28%	14%	7%	

rates of carbon accumulation of 1.7 tons ha^{-1} $year^{-1}$ (Justine et al., 2015) and 1 ton ha^{-1} $year^{-1}$ (Wang et al., 2013).

The carbon sequestration rate is typically greater in woody biomass than in soil herein. Considering the total carbon sequestration in vegetation only, the value for this study area (0.34 tons ha^{-1} $year^{-1}$) was greater than that estimated by Munoz-Rojas et al. (2011) from the analysis of the LULC changes over 51 years in southern Spain (0.039 tons ha^{-1} $year^{-1}$) and that reported by Tappeiner et al. (2008) covering 140 years of LULC changes in the Alpine valley area in Switzerland (0.04 tons ha^{-1} yr^{-1}). This result possibly reflects differences in cover types in each area, as well as in the types of changes observed over time and the different environmental and geographical contexts that affect the carbon sequestration rates in each vegetation cover type (Sil et al., 2017).

4.3. Carbon demands for sequestration

Tubiello et al. (2014) have reported the increase in the agricultural GHG emissions from all sources, and some sources, such as fertilizers, are increasing even more rapidly. Emission trends from 2001 to 2011 have revealed that enteric fermentation is the greatest contributor to agricultural emissions, followed by manure left on pastures, synthetic fertilizers, manure management, and organic soil cultivation (Tubiello et al., 2014). However, herein, organic soil (57%) emissions were greater than livestock (28%) emissions possibly because of the highest rate of land conversion to crop land in the catchment.

Gerber et al. (2013) have reported that livestock emissions accounted for 7.1 gigatons (GT) of carbon dioxide equivalent (CO_2-eq.) per year or 14.5% of all human-generated greenhouse release. The main sources of emissions included feed production and processing and digestion (84%) and manure decomposition (10%). The remainder was related to the processing and transportation of animal products. In this study, the estimated values were in agreement with these figures as enteric fermentation contributed to the dominant emission. Gerber et al. (2013) have also revealed that cattle mainly contribute to the sector's emissions with ~4.6 GT CO_2-eq., representing 65% of the sector emissions. Poultry and small ruminants exhibited considerably lower-emission levels, with each representing between 7% and 10% of sector emissions. Similarly, herein, 88.3% of the emissions were emitted from cattle, and the remaining livestock contributed to only 11.7% of the emission.

4.4. Carbon supply versus demand

The net map shown in Fig. 6 shows a location-specific overview of the status of carbon sequestration across the catchment LULC. It correlated the LULC carbon sequestration supply and demand balances to a positive or negative balance. The highest supply-to-demand was observed along the rivers and chains of the mountains in the upper and middle catchments where the highest woody biomass and soil carbon sequestration was available. Conversely, landscapes characterized by cereal crop lands and grazing lands with sparsely distributed trees exhibited a smaller negative net sequestration. Built-up areas with their different emission sources exhibited the highest negative net sequestration. Low carbon sequestration in built-up areas is typical, and a study in Austin, Texas, revealed that natural areas offset not >1.6% of the 2007 emissions (McCaw, 2012).

This study solely focuses on the balance between carbon sequestration and emission from different sources as the demand for sequestration within spatial units inside the catchment and neglects the spatial

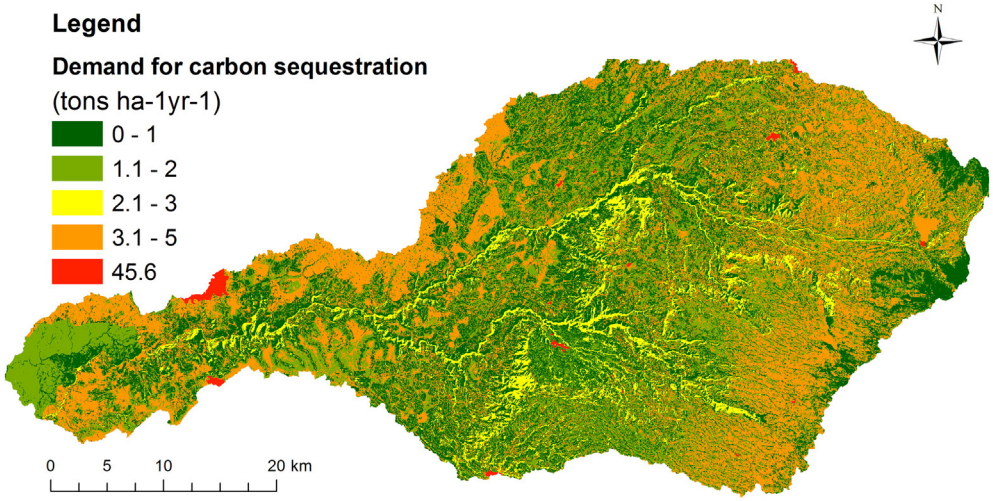

Fig. 5. Emission rates of GHG as proxy for estimating the demands for carbon sequestration.

Table 8
The supply and demands of carbon sequestration in the Wabe River catchment.

LULC	C Seq. (tons yr^{-1})	Emission (tons yr^{-1})	Net (tons yr^{-1})
Afro alpine vegetation	5482	611	4871
Bare land	7597	0	7597
Cereal crop	19,950	275,424	−255,474
Enset-based agroforestry	77,286	20,928	56,358
Forest land	45,714	40,655	5059
Grazing land	8350	178,920	−170,570
Shrub land	16,338	9430	6908
Built up area	132	36,512	−36,380
Wetland	0	0	0
Wood land	1903	640	1263
Total	182,752	563,120	−380,368

import and export of carbon sequestration on a large scale. Nonetheless, it is very useful and policy-relevant to assess the balance between the supply of and demand for this globally delivered service in a spatially explicit manner at the catchment level.

4.5. Implications for local policy makers and land use management

Even though global beneficiaries of carbon sequestration are available, such information can help policy makers and land managers to identify location-specific mechanisms for improving the supply and demand difference. For example, because of the removal of woody biomass to fire wood, conversion of land for farming and grazing, enteric fermentation and manure management from livestock manure, nitrogenous fertilizer consumption in cereal crop, and urbanization activities lead to GHG emissions above the carbon sequestration level in the Wabe River catchment. The following relevant approaches have been suggested to develop policies and strategies for reducing emissions without affecting the livelihood of the community, particularly for the identified net negative emission LULCs, to initiate the mitigation of the global climate change at the local level.

The woody biomass carbon stock in the Wabe River catchment varied with species, and the conservation of species with a large DBH was a valuable short-term strategy to contribute to climate regulation. In addition, the preservation of sacred (church) forests, trees planted in fences, and protecting trees in agricultural land are important for the regulation of not only the local climate but also the global climate. On account of its highest soil carbon storage capacity, the conservation of the Afro-Alpine vegetation areas can reduce emissions on the landscape scale. Enset-based agroforestry exhibited a good carbon sequestration, which is equivalent to high-vegetation areas. Thus, the promotion of this agroforestry will contribute not only to sustain the community's food security and sources of income but also to help reduce emissions (Mbow et al., 2014). A high carbon sequestration rate was observed for the forest land, woodland, and shrubland. The conservation of these vegetation types and introduction of alternative energy sources and fuel-efficient cooking and baking techniques would contribute to the reduction of the CO_2 emissions from other sources. The introduction of non-forest product uses would help to ensure that the economic basis of local communities is also strengthened.

In the Wabe River catchment, cereal crop and grazing land soils exhibited a comparably higher carbon stock than natural vegetation, which was even greater than eucalyptus plantations. The introduction of highly productive livestock systems based on indoor breeding and promoting cut and carry of grass biomass can decrease emissions in grazing land rather than herding large numbers of livestock in the field, which exhibit low productivity. These mechanisms also help in reducing carbon emissions from soil degradation because of overgrazing and in decreasing the demands of additional land for grazing. Approaches to increasing the productivity of cereal crops such as intensification of agriculture using improved seeds, better residue management, promoting natural fertilizers, lower-emission agricultural techniques, and irrigation schemes would also reduce carbon emissions. Such measures would also decrease the requirements in additional agricultural land that is primarily taken from vegetation covers and other land uses. Development of landfills and waste management facilities and the improvement of vehicle fuel efficiency by switching from kerosene to low-emission energy can decrease the net negative emissions in small catchment towns.

5. Conclusions

In this study, carbon storage and sequestration, as well as CO_2-eq. GHG emissions provided and emitted by agricultural, forest, and other land uses, was assessed by the differentiation of the supply and demand in a spatially explicit manner. Without the presence of high-emission industries and fossil fuel consumption, the CO_2 emissions were greater than the carbon sequestration rate in the catchment. Assessing services in this manner improved our understanding of the ecological capacity of different land uses and land cover (LULCs) to sequester and emit CO_2. This information aided in the identification of spatially explicit relationships between the supply and demand of regulating ecosystem services. Our approach aided the local policy and decision makers and land use planners to think about the ecosystem services in their decision making to increase the overall environmental quality. Such a supply–demand balance study could also considerably contribute to developing emission reduction strategies at different scales and embed them in their respective socio-ecological environment. Further studies were needed to

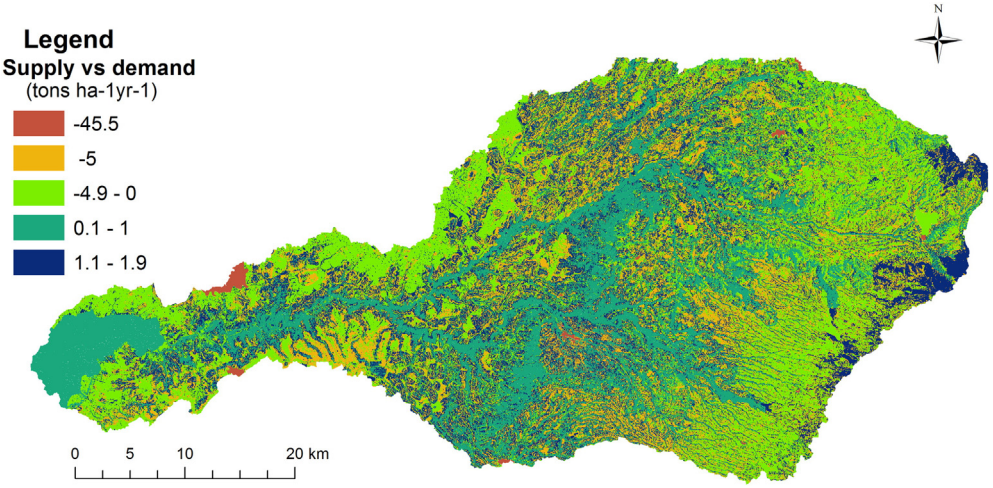

Fig. 6. Supply–demand carbon sequestration balance map of the Wabe River catchment.

explore the supply capacity and the demand of other regulating, provisioning, supporting, and cultural ecosystem services to develop well-integrated landscape planning approaches after analyzing the synergies and tradeoffs of the different land use alternatives.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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